Dublin Unified School District

Course Title:	Independent Study Calculus-based Electromagnetism
Grade Level(s):	12
Length of Course:	Two Semesters or Equivalent Term
Credit:	Ten Units (5.0 per semester)
Prerequisite:	Completion of AP Calculus & AP Physics Mechanics

Course Description:
This course is a rigorous college-level independent study **pass-or-fail** course, requiring extremely self-motivated learners; it is designed for students planning to specialize in a science or engineering major. The course focuses on topics of electricity and magnetism, such as: Electrostatics; Conductors, capacitors, dielectrics; Electric circuits; Magnetic Fields; and Electromagnetism. (The last month, students may also explore other topics such as heat and thermodynamics, wave behavior (light, sound, etc.), astronomy and some “modern” physics.) Calculus-based Physics students must: (a) develop a deep understanding of foundational principles of physics in classical electromagnetism by applying these principles to complex physical situations that combine multiple aspects of physics rather than present concepts in isolation; (b) design and conduct inquiry-based laboratory investigations to solve problems through first-hand observations, data collection, analysis and interpretation, and document these experiences; (c) develop critical thinking skills through applying methods of differential and integral calculus to formulate physical principles and solve complex physical problems. Use of a TI-graphing calculator is required for this course. **This course may not be taken for duplicate credit after Physics.

Schools Offering:	Dublin High School
Meets University of California Entrance Requirements:	not sought
Meets California State University Entrance Requirements:	not sought
Board Approval:	____________________
Instructional Materials:	Fundamentals of Physics, John Wiley & Sons, 2005 ISBN: 0-471-21643-7
Supplemental Materials:	Released Advanced Placement Exams

COURSE CONTENT:

Course Goals and/or Major Student Outcomes

This course is a rigorous college-level independent study course, requiring extremely self-motivated learners; it is designed for students planning to specialize in a science or engineering major. The course focuses on topics of electricity and magnetism, such as: Electrostatics; Conductors, capacitors, dielectrics; Electric circuits; Magnetic Fields; and Electromagnetism. (The last month, students may also explore other topics such as heat and thermodynamics, wave behavior (light, sound, etc.), astronomy and some "modern" physics.) Calculus-based Physics students must: (a) develop a deep understanding of foundational principles of physics in classical electromagnetism by applying these principles to complex physical situations that combine multiple aspects of physics rather than present concepts in isolation; (b) design and conduct inquiry-based laboratory investigations to solve problems through first-hand observations, data collection, analysis and interpretation, and document these experiences; (c) develop critical thinking skills through applying methods of differential and integral calculus to formulate physical principles and solve complex physical problems. A general outline of the course content can be seen below:

A. Electrostatics
   1. Charge and Coulomb's law
   2. Electric field and electric potential (including point charges)
   3. Gauss's law
   4. Fields and potentials of other charge distributions

B. Conductors, capacitors, dielectrics
   1. Electrostatics with conductors
   2. Capacitors
      a. Capacitance
      b. Parallel plate
      c. Spherical and cylindrical
   3. Dielectrics

C. Electric circuits
   1. Current, resistance, power
   2. Steady-state direct current circuits with batteries and resistors only
   3. Capacitors in circuits
      a. Steady state
      b. Transients in RC circuits

D. Magnetic Fields
   1. Forces on moving charges in magnetic fields
   2. Forces on current-carrying wires in magnetic fields
   3. Fields of long current-carrying wires
   4. Biot–Savart law and Ampere's law

E. Electromagnetism
   1. Electromagnetic induction (including Faraday's law and Lenz's law)
   2. Inductance (including LR and LC circuits)
   3. Maxwell's equations

COURSE OBJECTIVES:

A. Electrostatics

1. Charge and Coulomb's law

a) Students should understand the concept of electric charge, so they can:

1) Describe the types of charge and the attraction and repulsion of charges.
2) Describe polarization and induced charges.

b) Students should understand Coulomb's law and the principle of superposition, so they can:

1) Calculate the magnitude and direction of the force on a positive or negative charge due to other specified point charges.
2) Analyze the motion of a particle of specified charge and mass under the influence of an electrostatic force.

2. Electric field and electric potential (including point charges)

a) Students should understand the concept of electric field, so they can:

1) Define it in terms of the force on a test charge.
2) Describe and calculate the electric field of a single point charge.
3) Calculate the magnitude and direction of the electric field produced by two or more point charges.
4) Calculate the magnitude and direction of the force on a positive or negative charge placed in a specified field.
5) Interpret an electric field diagram.
6) Analyze the motion of a particle of specified charge and mass in a uniform electric field.

b) Students should understand the concept of electric potential, so they can:

1) Determine the electric potential in the vicinity of one or more point charges.
2) Calculate the electrical work done on a charge or use conservation of energy to determine the speed of a charge that moves through a specified potential difference.
3) Determine the direction and approximate magnitude of the electric field at various positions given a sketch of equipotentials.
4) Calculate the potential difference between two points in a uniform electric field, and state which point is at the higher potential.
5) Calculate how much work is required to move a test charge from one location to another in the field of fixed point charges.
6) Calculate the electrostatic potential energy of a system of two or more point charges, and calculate how much work is required to establish the charge system.

7) Use integration to determine electric potential difference between two points on a line, given electric field strength as a function of position along that line.

8) State the general relationship between field and potential, and define and apply the concept of a conservative electric field.

3. **Gauss's law**

a) Students should understand the relationship between electric field and electric flux, so they can:

1) Calculate the flux of an electric field through an arbitrary surface or of a field uniform in magnitude over a Gaussian surface and perpendicular to it.

2) Calculate the flux of the electric field through a rectangle when the field is perpendicular to the rectangle and a function of one coordinate only.

3) State and apply the relationship between flux and lines of force.

b) Students should understand Gauss's law, so they can:

1) State the law in integral form, and apply it qualitatively to relate flux and electric charge for a specified surface.

2) Apply the law, along with symmetry arguments, to determine the electric field for a planar, spherical or cylindrically symmetric charge distribution.

3) Apply the law to determine the charge density or total charge on a surface in terms of the electric field near the surface.

4. **Fields and potentials of other charge distributions**

a) Students should be able to use the principle of superposition to calculate by integration:

1) The electric field of a straight, uniformly charged wire.

2) The electric field and potential on the axis of a thin ring of charge, or at the center of a circular arc of charge.

3) The electric potential on the axis of a uniformly charged disk.

b) Students should know the fields of highly symmetric charge distributions, so they can:

1) Identify situations in which the direction of the electric field produced by a charge distribution can be deduced from symmetry considerations.

2) Describe qualitatively the patterns and variation with distance of the electric field of:

a. Oppositely-charged parallel plates.

b. A long, uniformly-charged wire, or thin cylindrical or spherical shell.

3) Use superposition to determine the fields of parallel charged planes, coaxial cylinders or concentric spheres.

4) Derive expressions for electric potential as a function of position in the above cases.

B. Conductors, capacitors, dielectrics

1. Electrostatics with conductors

a) Students should understand the nature of electric fields in and around conductors, so they can:

1) Explain the mechanics responsible for the absence of electric field inside a conductor, and know that all excess charge must reside on the surface of the conductor.

2) Explain why a conductor must be an equipotential, and apply this principle in analyzing what happens when conductors are connected by wires.

3) Show that all excess charge on a conductor must reside on its surface and that the field outside the conductor must be perpendicular to the surface.

b) Students should be able to describe and sketch a graph of the electric field and potential inside and outside a charged conducting sphere.

c) Students should understand induced charge and electrostatic shielding, so they can:

1) Describe the process of charging by induction.

2) Explain why a neutral conductor is attracted to a charged object.

3) Explain why there can be no electric field in a charge-free region completely surrounded by a single conductor, and recognize consequences of this result.

4) Explain why the electric field outside a closed conducting surface cannot depend on the precise location of charge in the space enclosed by the conductor, and identify consequences of this result.

2. Capacitors

a) Students should understand the definition and function of capacitance, so they can:

1) Relate stored charge and voltage for a capacitor.

2) Relate voltage, charge and stored energy for a capacitor.

3) Recognize situations in which energy stored in a capacitor is converted to other forms.

b) Students should understand the physics of the parallel-plate capacitor, so they can:

1) Describe the electric field inside the capacitor, and relate the strength of this field to the potential difference between the plates and the plate separation.

2) Relate the electric field to the density of the charge on the plates.

3) Derive an expression for the capacitance of a parallel-plate capacitor.
4) Determine how changes in dimension will affect the value of the capacitance.
5) Derive and apply expressions for the energy stored in a parallel-plate capacitor and for the energy density in the field between the plates.
6) Analyze situations in which capacitor plates are moved apart or moved closer together, or in which a conducting slab is inserted between capacitor plates, either with a battery connected between the plates or with the charge on the plates held fixed.

c) Students should understand cylindrical and spherical capacitors, so they can:

1) Describe the electric field inside each.
2) Derive an expression for the capacitance of each.

3. Dielectrics

Students should understand the behavior of dielectrics, so they can:

a) Describe how the insertion of a dielectric between the plates of a charged parallel-plate capacitor affects its capacitance and the field strength and voltage between the plates.

b) Analyze situations in which a dielectric slab is inserted between the plates of a capacitor.

C. Electric circuits

1. Current, resistance, power

a) Students should understand the definition of electric current, so they can relate the magnitude and direction of the current to the rate of flow of positive and negative charge.

b) Students should understand conductivity, resistivity and resistance, so they can:

1) Relate current and voltage for a resistor.
2) Write the relationship between electric field strength and current density in a conductor, and describe, in terms of the drift velocity of electrons, why such a relationship is plausible.
3) Describe how the resistance of a resistor depends upon its length and cross-sectional area, and apply this result in comparing current flow in resistors of different material or different geometry.
4) Derive an expression for the resistance of a resistor of uniform cross-section in terms of its dimensions and the resistivity of the material from which it is constructed.
5) Derive expressions that relate the current, voltage and resistance to the rate at which heat is produced when current passes through a resistor.
6) Apply the relationships for the rate of heat production in a resistor.

2. **Steady-state direct current circuits with batteries and resistors only**

a) Students should understand the behavior of series and parallel combinations of resistors, so they can:

1) Identify on a circuit diagram whether resistors are in series or in parallel.

2) Determine the ratio of the voltages across resistors connected in series or the ratio of the currents through resistors connected in parallel.

3) Calculate the equivalent resistance of a network of resistors that can be broken down into series and parallel combinations.

4) Calculate the voltage, current and power dissipation for any resistor in such a network of resistors connected to a single power supply.

5) Design a simple series-parallel circuit that produces a given current through and potential difference across one specified component, and draw a diagram for the circuit using conventional symbols.

b) Students should understand the properties of ideal and real batteries, so they can:

1) Calculate the terminal voltage of a battery of specified emf and internal resistance from which a known current is flowing.

2) Calculate the rate at which a battery is supplying energy to a circuit or is being charged up by a circuit.

c) Students should be able to apply Ohm's law and Kirchhoff's rules to direct-current circuits, in order to:

1) Determine a single unknown current, voltage or resistance.

2) Set up and solve simultaneous equations to determine two unknown currents.

d) Students should understand the properties of voltmeters and ammeters, so they can:

1) State whether the resistance of each is high or low.

2) Identify or show correct methods of connecting meters into circuits in order to measure voltage or current.

3) Assess qualitatively the effect of finite meter resistance on a circuit into which these meters are connected.

3. **Capacitors in circuits**

a) Students should understand the $t = 0$ and steady-state behavior of capacitors connected in series or in parallel, so they can:

1) Calculate the equivalent capacitance of a series or parallel combination.

2) Describe how stored charge is divided between capacitors connected in parallel.

3) Determine the ratio of voltages for capacitors connected in series.

4) Calculate the voltage or stored charge, under steady-state conditions, for a capacitor connected to a circuit consisting of a battery and resistors.

b) Students should understand the discharging or charging of a capacitor through a resistor, so they can:

1) Calculate and interpret the time constant of the circuit.

2) Sketch or identify graphs of stored charge or voltage for the capacitor, or of current or voltage for the resistor, and indicate on the graph the significance of the time constant.

3) Write expressions to describe the time dependence of the stored charge or voltage for the capacitor, or of the current or voltage for the resistor.

4) Analyze the behavior of circuits containing several capacitors and resistors, including analyzing or sketching graphs that correctly indicate how voltages and currents vary with time.

D. Magnetic Fields

1. Forces on moving charges in magnetic fields

Students should understand the force experienced by a charged particle in a magnetic field, so they can:

a) Calculate the magnitude and direction of the force in terms of q, $\vec{v}$, and $\vec{B}$, and explain why the magnetic force can perform no work.

b) Deduce the direction of a magnetic field from information about the forces experienced by charged particles moving through that field.

c) Describe the paths of charged particles moving in uniform magnetic fields.

d) Derive and apply the formula for the radius of the circular path of a charge that moves perpendicular to a uniform magnetic field.

e) Describe under what conditions particles will move with constant velocity through crossed electric and magnetic fields.

2. Forces on current-carrying wires in magnetic fields

Students should understand the force exerted on a current-carrying wire in a magnetic field, so they can:

a) Calculate the magnitude and direction of the force on a straight segment of current-carrying wire in a uniform magnetic field.

b) Indicate the direction of magnetic forces on a current-carrying loop of wire in a magnetic field, and determine how the loop will tend to rotate as a consequence of these forces.

c) Calculate the magnitude and direction of the torque experienced by a rectangular loop of wire carrying a current in a magnetic field.

3. Fields of long current-carrying wires

Students should understand the magnetic field produced by a long straight current-carrying wire, so they can:

a) Calculate the magnitude and direction of the field at a point in the vicinity of such a wire.

b) Use superposition to determine the magnetic field produced by two long wires.

c) Calculate the force of attraction or repulsion between two long current-carrying wires.

4. Biot-Savart law and Ampere's law

a) Students should understand the Biot-Savart law, so they can:

1) Deduce the magnitude and direction of the contribution to the magnetic field made by a short straight segment of current-carrying wire.

2) Derive and apply the expression for the magnitude of $\vec{B}$ on the axis of a circular loop of current.

b) Students should understand the statement and application of Ampere's law in integral form, so they can:

1) State the law precisely.

2) Use Ampere's law, plus symmetry arguments and the right-hand rule, to relate magnetic field strength to current for planar or cylindrical symmetries.

c) Students should be able to apply the superposition principle so they can determine the magnetic field produced by combinations of the configurations listed above.

E. Electromagnetism

1. Electromagnetic induction (including Faraday's law and Lenz's law)

a) Students should understand the concept of magnetic flux, so they can:

1) Calculate the flux of a uniform magnetic field through a loop of arbitrary orientation.

2) Use integration to calculate the flux of a non-uniform magnetic field, whose magnitude is a function of one coordinate, through a rectangular loop perpendicular to the field.

b) Students should understand Faraday's law and Lenz's law, so they can:

1) Recognize situations in which changing flux through a loop will cause an induced emf or current in the loop.

2) Calculate the magnitude and direction of the induced emf and current in a loop of wire or a conducting bar under the following conditions:

a. The magnitude of a related quantity such as magnetic field or area of the loop is changing at a constant rate.

b. The magnitude of a related quantity such as magnetic field or area of the loop is a specified non-linear function of time.

c) Students should be able to analyze the forces that act on induced currents so they can determine the mechanical consequences of those forces.

2. Inductance (including *LR* and *LC* circuits)

a) Students should understand the concept of inductance, so they can:

1) Calculate the magnitude and sense of the emf in an inductor through which a specified changing current is flowing.
2) Derive and apply the expression for the self-inductance of a long solenoid.

b) Students should understand the transient and steady state behavior of DC circuits containing resistors and inductors, so they can:

1) Apply Kirchhoff's rules to a simple *LR* series circuit to obtain a differential equation for the current as a function of time.
2) Solve the differential equation obtained in (1) for the current as a function of time through the battery, using separation of variables.
3) Calculate the initial transient currents and final steady state currents through any part of a simple series and parallel circuit containing an inductor and one or more resistors.
4) Sketch graphs of the current through or voltage across the resistors or inductor in a simple series and parallel circuit.
5) Calculate the rate of change of current in the inductor as a function of time.
6) Calculate the energy stored in an inductor that has a steady current flowing through it.

3. Maxwell's equations

Students should be familiar with Maxwell's equations so they can associate each equation with its implications.

Key Assignments, Labs, and/or Activities

Since this course is independent study, students will be using textbooks and available online content to meet the objectives listed above, with an approximate pace set by the instructor. Success will be determined by student scores on available released AP Electromagnetism exams.

As much as possible (when laboratory supplies can be secured, and when the activities can be done individually) students will be asked to conduct appropriate laboratory activities. Included in those activates will be a pre-lab & lab write-up as seen below:

A. Pre-lab activities for students include all of the following:

1. Written assignment in which students will be asked to explain and describe, in their own words, physical phenomena, make predictions about what one should or should not observe given the laws of physics, and evaluate the assumptions behind the usage of various physical equations. Students will also model physical situations mathematically, and perform rigorous, often-multi-step, calculations using trigonometry, algebra, and geometry.

2. Ensure awareness of safety rules, when to use safety equipment such as safety goggles, and appropriate and correct use of special equipment such as electric power supplies.

B. Lab write-up

1. In their lab reports, students will be asked to describe, in detail, the purpose of each activity, the nature of theory or principle being investigated, the procedure they used, conclusions reached, whether conclusions were consistent with predictions made based on the accepted laws of physics, and the nature of any sources of uncertainty or measurement error in the lab. Each lab report will also include all data taken during the lab, and full graphical and mathematical analysis of the data.

Specific Laboratory activities may include:

- *Topographic Mapping Lab*: Students use water levels around a plastic mountain model to draw the topographic lines for the mountain. They are then asked questions to prepare them for similar concepts on lines of equipotential, gradient and electric fields.
- *Electric Potential Mapping Lab:* Using conductive ink pens, students will create and test a variety of conductive patterns on a sheet of resistive paper. They will use a voltage probe to measure the magnitude and sign of the electric potential at a variety of key locations. They will use their results to sketch equipotential surfaces and to determine electric fields around the conductors.
- *Charging and Discharging a Capacitor Lab:* Students will construct a basic resistor and capacitor DC circuit using breadboards with stock capacitors and resistors. They will use a Pasco voltage probe to measure the voltage across the capacitor as a function of time for both charging and discharging cases. For long time-constant circuits (5-30 seconds,) students will obtain a single voltage-time dataset. For short time-constant circuits (<1 second) students will use the voltage probe in "oscilloscope" mode to again determine time constant based on percent charge or discharge.
- *Home-built Capacitor lab:* Students will construct a capacitor from paper and aluminum foil. They will determine the time constant by using a function generator and Pasco voltage probe.
- *Combining Capacitors in Series and Parallel Lab:* Students will construct a variety of series, parallel and combination circuits involving capacitors. They will use a digital multimeter to measure voltage drops across capacitors in these networks, and will compare their results to theoretical predictions.
- *Resistivity of a Slinky Lab:* In this lab students will investigate the relationship between the resistance and length of a toy Slinky. They will use a digital ohmmeter to determine resistance as a function of the number of coils.
- *Ohmic Material Lab:* Students will make a series of measurements of current versus applied voltage for a light-bulb filament in order to determine if the filament displays ohmic behavior. They will construct a graph of current versus voltage and will use it to justify their conclusion. They will correctly discuss the behavior in terms of the increase of resistance with temperature in most metals.
- *Internal Resistance Lab:* Students will use a battery in combination with a low-resistance, high-power resistor in order to determine the internal resistance of the battery. In this lab, students will be required to demonstrate proper usage of both a voltmeter an ammeter.

- *Series and Parallel Circuits Lab:* Students will construct series circuits, parallel circuits and combination networks using a set of stock carbon resistors on a prototyping breadboard. They will measure voltage drops across resistors, current through resistors, and equivalent resistance of networks, using a standard digital multimeter probe (acts as voltmeter, ammeter and ohmmeter.)
- *DC Motor Lab:* Students will apply principles of force acting on a current loop in a uniform magnetic field to design, construct and test a simple DC motor, using a battery, length of insulated wire, and small permanent magnet. Student motors will have a 50% duty cycle, achieved by using a permanent marker to shut off current for half of a turn.
- *Helmholtz Coil Lab:* Students will construct Helmholtz coils using wire and cardboard discs. They will use a Hall probe to measure the magnetic field along the axis of these coils when a DC current is applied, comparing field magnitudes and directions to theoretical predictions.
- *Slinky Solenoid Lab:* Students will use a Hall probe to measure the magnitude and direction of the magnetic field generated within a toy Slinky. They test the relationship between field strength and the number of coils per unit length. They will also determine the permeability constant.
- *Induction Lab:* Students will explore a variety of concepts relating to Faraday's law, and electromagnetic induction by exploring stations at which they investigate how changing magnetic fields induce EMFs. They will use Lenz's law to predict the direction of the flow of induced current when a bar magnet is moved into and out of a solenoid, comparing these results to the current induced in a neighboring solenoid that is hooked up to a power supply. Students will also explore magnetic braking by analyzing the motion of a magnet dropped through a copper tube, and will investigate the repulsion of an aluminum ring when placed over a changing field core.
- *RL Circuit Lab:* Students use a signal generator to generate a positive square-wave voltage supply. They then use a Pasco voltage sensor to measure the varying voltage across the resistor of an RL circuit. By doing this they can analyze the time constant of the circuit.

Instructional Methods and/or Strategies

- Online lectures & material
- Individual work/problem solving
- Laboratory investigations

Assessment Methods and/or Tools

- Pass or Fail
- Informal assessment of in-class problem solving
- Released AP Electromagnetism Exam
- Lab reports

Assessment Criteria

- Mastery of concepts
- Ability to perform calculations correctly
- Ability to communicate concepts and calculations in writing